

HURRICANE SURGE FREQUENCY ESTIMATED FOR THE GULF COAST OF TEXAS

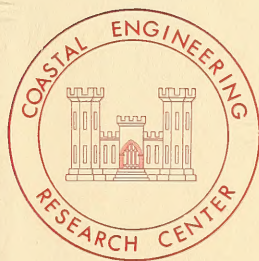


by

B. R. Bodine

TECHNICAL MEMORANDUM NO. 26

February 1969



U. S. ARMY
CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

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ABSTRACT

Nineteen hurricanes of record since 1900 are used to derive a surge-frequency relationship representative of the entire Texas Coast. Pure statistical methods were not used because of the small number of recorded hurricanes and the lack of recorded data from early storms. The available data are treated by logic and reasoning to derive probable surge frequencies.

A method is proposed for assigning frequencies to water levels of hypothetical hurricanes with various prescribed values of hurricane parameters - central pressure index, forward speed, and radius of maximum winds. Also a method is presented for estimating surge frequency in inland bays and adjacent regions subject to flooding by hurricanes.

Results are presented in tables and curves. As new data become available, the developed curves can be refined.

FOREWORD

CERC is publishing this report to provide coastal engineers with a method of predicting return frequencies of hurricanes crossing the Texas Coast. The paper also gives a direct approach to the problems of surge heights along the open coast and in semiencllosed bays.

The author, B. R. Bodine, transferred to the Coastal Engineering Research Center from the Galveston District, U. S. Army Corps of Engineers, Galveston, Texas. The preliminary report was prepared at Galveston; this final version was prepared at CERC under the supervision of George M. Watts, Chief of the Engineering Development Division.

The author expresses his appreciation to J. W. Woodward of the Galveston District, and to L. R. Beard, Chief of the Hydrologic Engineering Center, Sacramento District, Corps of Engineers, for their assistance and suggestions.

At the time of publication, Lieutenant Colonel Myron Dow Snoke was Director of CERC; Joseph M. Caldwell was Technical Director.

NOTE: Comments on this publication are invited. Discussion will be published in the next issue of the CERC Bulletin.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945, as supplemented by Public Law 172, 88th Congress, approved November 7, 1963.

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HURRICANE SURGE FREQUENCY: ESTIMATED FOR THE GULF COAST OF TEXAS

Section I. INTRODUCTION

Dangerous and destructive tropical cyclones (hurricanes) can be expected to cross the Texas Coast on the average of about once every three years. In the present century alone, twenty full-scale hurricanes have hit this coast, some were extremely severe, others less severe, but all were destructive. The great storm of 1900 stands above all others, because it took the lives of about 6,000 people on Galveston Island. Had major steps not been taken with respect to storm warnings and deployment of hurricane protection systems, it would surely have been possible for the later, more severe hurricanes to cause considerably more deaths than the 1900 storm. Seawalls were constructed along the beach fronting the city of Galveston, and this line of protection has prevented any recurrence of a catastrophe with an order of magnitude of the 1900 hurricane. Over the past several decades, tropical cyclones have caused property damages that ran into billions of dollars. Hurricane Carla (1961) caused damages in excess of \$400 million. The hurricanes which cross the coast with an average frequency of about once in three years have taken a high toll in human lives and property damage.

Although strong hurricane winds and the tornadoes spawned during the course of the hurricane cause great loss of life and property, the high surge produced is the most destructive component on the Texas Coast. In general this is because the land slopes gently from the sea toward the hinterland. The violent winds associated with a hurricane drive the sea over the low-lying terrain into the shallow bays, rivers, and tributary streams. A single severe hurricane can flood vast land areas. For example, Hurricane Carla (1961) flooded more than 1.5 million acres of land. The abnormal rise of the sea surface on the Texas Coast brought about by tropical hurricanes is indeed the most destructive factor.

Coastal engineers must design hurricane-flood protection projects to combat the onslaught of tropical cyclones in order to protect lives and property. To accomplish this mission, the engineer not only must know how high the surges will be for the expected future hurricanes, but also the frequency of their return. In other words, a design surge must be prescribed when levee and seawall heights are to be established, and the frequency of this surge must be estimated. Surge heights and related frequencies must also be estimated for those storms that fall below the one chosen for the design so that economic feasibility studies can be carried out. Clearly, the line of protection should not be designed in such a manner that total failure could occur during a very severe and infrequent hurricane. Thus the coastal engineer should have some insight in the maximum probable surge height and its associated frequency. Consequently, the coastal engineer must be able to predict the surge heights over a wide spectrum as well as the related return frequencies to obtain the best design for hurricane-flood protection works, from the standpoint of safety and cost.

In this investigation, surge frequency estimates are based on actual hurricanes of record, but extended by logic and mathematical relations to cover hypothetical hurricanes. Nineteen actual hurricanes, experienced on the Texas Coast over a period of 66 years of record (1900-1965) are used in conjunction with this analysis. These hurricanes were selected because the parameters which define the storm intensity have been historically recorded, and because, in the derivation of the hypothetical hurricane model, a parametric study is employed. If there were sufficient data of surge heights at all desirable locations in the sea and in adjoining bays and low-lying terrain, it would be better indeed to treat such a problem by the methods described in pure statistics. However, this is not the case because recorded surge heights are meager, tide recording stations are limited in number, and the years of record are relatively few. Therefore, it is not only necessary, but mandatory, to resort to methods of logic or reasoning for resolution of the problem.

The present study originated in connection with the authorized Texas Coast Hurricane Studies because of the difficulties encountered in deriving surge frequency estimates for various locations within Galveston Bay. It would indeed be more appropriate to base surge-frequency relationships within the bay system on actual records; however, only two water-level recording stations located near Galveston Island have records adequate for carrying out this type of analysis. Since these recorders are located in the lower region of the bay and near the eastern part of the island, they give no indication of surge-frequency relationships in other parts of the bay. Water surface elevations in a semienclosed bay can vary significantly throughout the bay, and the extent of variation is dependent upon the geometry of the basin and the forcing functions involved. To resolve the problem, the surge frequency must be determined at numerous positions within the confines of the estuary. Because of insufficient observed water levels in Galveston Bay, the surge frequencies at all locations of interest must be determined from hurricane surge heights resolved from a numerical scheme using prescribed hurricane parameters. Resolution of the surge heights in Galveston Bay has been treated by Reid and Bodine (1968) by employing a finite-difference numerical method for solving the linearized hydrodynamic transport equations. The parametric studies related to the above work can be used in determining the surge frequencies at various positions within the bay.

The surge frequencies that may be expected for hurricanes in a bay system are coupled with the surge frequencies on the open coast for a particular location. The amplitude of the surge, however, can vary significantly from a position in the sea to a position in the bay. Marinos and Woodward (1968) used those parameters that govern the intensity of a hurricane in conjunction with the Bathystrophic Storm Tide theory* to predict the surge that may be expected from hypothetical hurricanes at the open coast of Texas.

*Bathystrophic Storm Tide theory takes into account the coriolis effect on the wind stress as it acts on the water.

The surge elevations determined from this investigation will be used in development of the open-coast surge frequency. The following terminology is introduced to give special meaning to a hypothetical hurricane with a central pressure index (CPI) frequency probability of once in 100 years. A hurricane possessing this particular characteristic will be designated as a "Beta Hurricane" and included in this type of hypothetical hurricane is the Standard Project Hurricane (SPH). The Beta Hurricane is an SPH if, and only if, the storm generates the maximum surge at a specific location under investigation. Maximum surges are, of course, produced by an appropriate combination of all parameters involved for the particular basin under consideration. The "Standard Project Hurricane" as defined by the Corps of Engineers is the most severe storm that is *reasonably characteristic* of the location being investigated.

Historically, it does not appear from a study of past hurricane records that storms occur more frequently at any specific location along the Texas Coast than at any other. On this basis, and for the purposes of this study, it will be assumed that hurricanes approach and cross the coast uniformly.

Section II. OPEN-COAST SURGE FREQUENCY

1. General

In the development of the open-coast surge frequencies, it is considered that the disturbance of the sea surface can be separated into three component parts or causes, i.e., hurricane winds, other high winds, and astronomical forces, although these are actually inseparable. Maximum surge heights which have been produced, but are less than 2 feet above the mean sea level datum are disregarded in the present study. Water level elevations in this range can be attributed primarily to light winds and the astronomical forces. Very high surges are produced by hurricanes, and surges lying in the range of two feet to the high surges, and caused by strong winds and tropical depressions, are designated a non-hurricane surge. Of course, there is considerable overlap of hurricane surges into the non-hurricane surge range, however, these can be combined in the final analysis. A hurricane is a storm that has cyclonic wind patterns and has maximum wind velocities that equal or exceed 75 miles per hour.

2. Historical Hurricane Data

Many hurricanes of record approached and crossed the Texas Coast prior to the 20th century. The data of surge heights and hurricane parameters for these early storms are so limited that they would be ineffectual in the present study. Since 1900, great strides have been taken to record the various characteristics of hurricanes, and the art of measurement and procurement of the data has improved substantially over the years.

Nineteen full-scale hurricanes covering a period of 66 years are used in this investigation. Hurricane Beulah (1967) is not included in this analysis due to incomplete examination of the data available at this time. Table 1 shows the peak surge heights (i.e., the highest water elevation reached on the open coast) and hurricane parameters for all 19 storms. Some of the peak surges indicated in the Table were obtained by transposition and adjustment of surge heights recorded in adjacent estuaries and coastal streams.

3. Surge Profile

A hurricane that moves over the Continental Shelf and approaches the coast piles up water at the shore over long reaches of the coastline. The extent or breadth of the coast affected is dependent upon the hurricane parameters involved and the basin characteristics. The peak open-coast surge usually occurs at the point of landfall of the region of maximum winds (i.e., if the hurricane approaches normal or somewhat normal to the coastline), and lesser surges are produced to the left and right of the peak or maximum storm surge. In the development of frequencies for hurricane surges for some specific position it is necessary to include the peak surges as well as all lesser surges which occur at that location. This simply means that surge profiles are required for all hurricanes used in the surge frequency investigations.

Although peak surge heights are known for the 19 hurricanes, only limited information is available on the maximum water levels reached on the coast adjacent to the peak surges, and this limited information is based on observations of only the most recent storms. The most documented storm in this respect is Hurricane Carla (1961), which provided the necessary data for establishing a relationship of surge versus distance (profile) along the Texas Coast. The surge profile for this storm revealed that the maximum water levels to the right and to the left of the peak surge varied, for all practical purposes, linearly with distance along the coast. The slopes of the surge profile to the left and right of the peak surge, however, were appreciably different, as could be expected from the characteristics of a hurricane.

Other storms with known surge heights to the left and right of the peak surge were also used in deriving surge profiles. It was found that the linear relationship was prevalent for all storms used, and the slopes remained essentially constant with the vertical departure of the surge height, dependent upon the magnitude of the peak surge elevation. Typical surge-profile curves derived from this analysis are indicated in Figure 1. The terms *left* and *right* in the figure, are directions as seen from the sea. The typical surge profiles indicated on Figure 1 will not hold true for hurricanes approaching and crossing the coast at small angles to the coastline. For example, Hurricane Beulah (1967) approached and crossed the shore near Brownsville, Texas, at an angle of approximately 15 degrees from the coastline, and preliminary observations of water level elevations indicate that a lesser surge occurred at the point of landfall of the region of maximum winds than to the left and right of this position.

TABLE 1

TEXAS HURRICANES OF RECORD

Approximate Location of Landfall	Date of Landfall	CPI (inches of Mercury)	R (N.M.)	V _F (Knots)	Peak * Surge (ft. MSL)	P Years**
Galveston	8 Sep 1900	27.64	14	10	11.0	280
Freeport	21 Jul 1909	28.31	19	12	9.0	16
Galveston	16 Aug 1915	28.14	32	11	12.7	8
Mustang Island	18 Aug 1916	28.00	35	11	9.2	7
Port Aransas	14 Sep 1919	28.00	20	20	11.1	184
Port O'Connor	22 Jun 1921	28.17	17	11	7.1	13
Port O'Connor	28 Jun 1929	28.62	13	15	3.0	63
Freeport	13 Aug 1932	27.83	12	15	6.1	792
Port Isabel	4 Aug 1933	28.80	25	10	4.5	11
Port Isabel	5 Sep 1933	28.02	20	8	11.0	93
Galveston	7 Aug 1940	28.76	11	8	2.1	135
Freeport	23 Sep 1941	28.31	21	13	9.5	17
Port O'Connor	30 Aug 1942	28.07	18	14	10.0	38
Port Bolivar	27 Jul 1943	28.78	16	8	3.0	22
Port Aransas	27 Aug 1945	28.57	18	4	9.0	52
Freeport	4 Oct 1949	28.88	28	11	7.8	3
Galveston	25 Jun 1959	29.07	17	5	2.8	43
Port O'Connor	11 Sep 1961	27.64	26	4	12.3	289
High Island	17 Sep 1963	29.41	30	10	4.2	3

* Estimated peak surge height on the open coast.

** Estimated number of years between events.

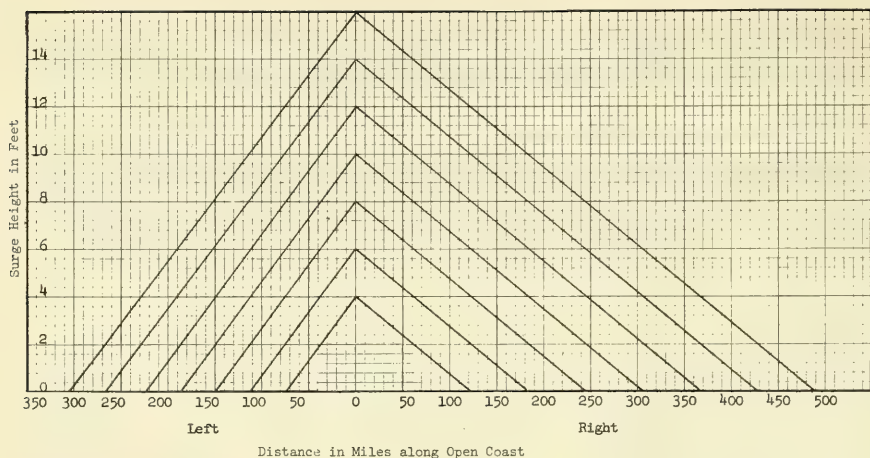


Figure 1. Typical Surge Profile Along Texas Gulf Coast

This storm, of course, could be included in the surge frequency analysis when the final surge profile has been established. For the sake of simplicity, and because the actual surge profiles are unknown for several of the hurricanes used in this investigation, it is assumed that these storms will have the form of the typical surge profiles. At the extreme ends of the surge-profile curves, the relationship can become meaningless since a position is reached where linearity ceases because the influence of the storm at sea at great distances from the center is small. Because of this and to ensure retaining the property of linearity, the coastline distance included in the surge profile relationship must be bounded to the left and right of the peak surge. A mathematical relation is given in the following paragraph for describing these limits.

It is possible to derive formulas and useful relations for analytically predicting the surge heights at coastal locations for full-scale hurricanes based on the linear typical surge profile curves. The surge height at the right and left of the peak surge is given by:

$$H_R = H_P - 0.0328 S_R \quad (1)$$

$$H_L = H_P - 0.0526 S_L \quad (2)$$

where H is the surge height in feet, S is the distance in nautical miles measured from the peak surge to the surge to be computed, subscript P indicates that the open-coast surge height is the peak water level or highest water level produced during the course of a single storm, and subscripts R and L denote positions right and left of the peak surge.

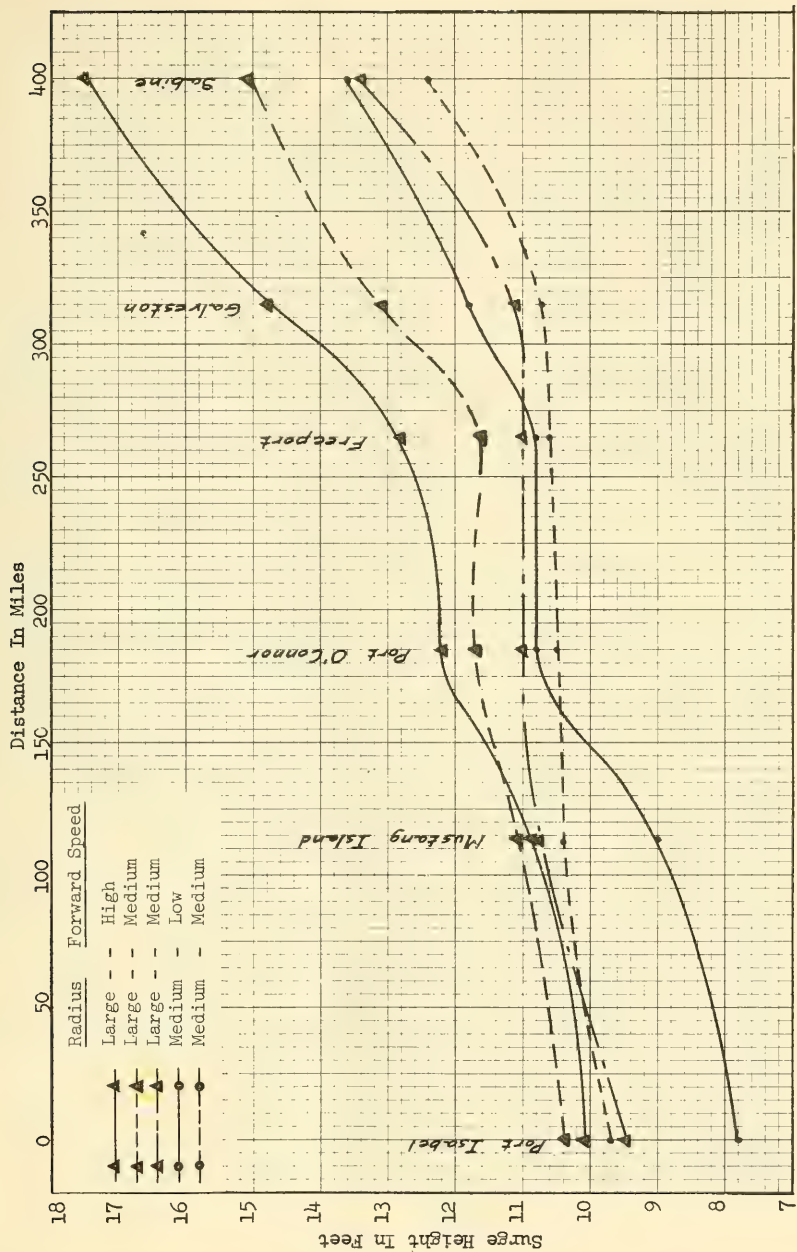


Figure 2. Beta Hurricane Surge Heights

It can also be shown that if two surge heights are known, one to the left and one to the right of the peak surge, then the peak surge height is

$$H_P = (S_T + 30.67 H_R + 19.01 H_L)/49.68 \quad (3)$$

where S_T is the total distance measured along the coastline between the points where H_R and H_L were reckoned. This can also be extended to finding the position of the peak surge on the coastline by either of the following relations:

$$\begin{aligned} S_R &= 30.67 (H_P - H_R) \\ S_L &= 19.01 (H_P - H_L) \end{aligned} \quad (4)$$

While developing surge-height profiles based on actual data, it was noted that the curves exhibited a tendency to flatten out as the distance along the coastline reached a position far to the left and right of the peak surge. However, it was found that the relationship remained essentially linear if these distances were limited to:

$$S_R \leq 24.4 H_P \quad (5)$$

$$S_L \leq 15.0 H_P \quad (6)$$

Surge heights lying beyond this range, or at the outer periphery of the hurricane are included implicitly in the water levels for nonhurricanes which will be covered later.

4. Computed Surge Heights

Beta Hurricane surge heights used in connection with this study are based on those determined by Marinos and Woodward (1968) for the entire Texas Coast. These surge heights were computed based on previously developed theory that was extended by Freeman, Baer, and Jung (1957) to take into account the bathystrophic effect or longshore component of flow caused by the Coriolis force. Calibration of the numerical analogs of the basic differential equations of fluid motion, appropriate to the problem was carried out by adjustment of the seabed friction factor for each basin investigated. Verification of reasonable calibration was achieved by making comparisons of the computed surge heights to those that actually occurred for various hurricanes of record. After adequate calibration, the equations were used for predicting the surge heights that would be expected from hypothetical hurricanes (i.e., of the Beta type) by variation of the parameters, radius of maximum winds (R), and forward speed V_P . The results of this investigation are indicated on Figure 2. The radius of maximum winds is the distance from the eye of the hurricane to the place where surface wind velocities are maximum; this parameter reflects the areal extent of the storm. There is a general tendency for R to exhibit a partial relationship to the CPI

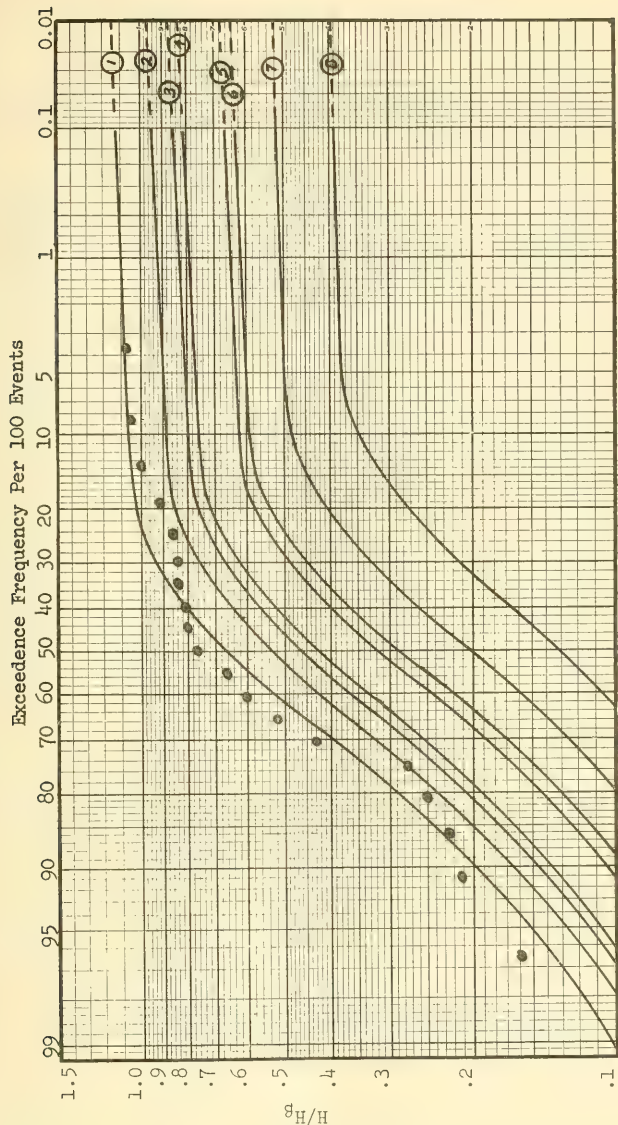


Figure 3. Frequency of Hurricane Surge on Open Texas Coast

(as can be shown graphically), although there is a wide range of scatter of the points. However, it appears from this relationship that R has a tendency to decrease for increasing storm intensity (lower values of CPI). The forward speed, the rate of movement of the hurricane eye, is apparently independent of both R and CPI. Values of R range from about 11 to 35 nautical miles; V_F values range from 4 to 28 knots. If only the integer values of the parameters in the ranges given above are used, 25 x 25 or 625 combinations could be formed. Based on this fact, Graham and Nunn (1959) reduced the number of values to be considered for developing the SPH surge by specifying three values each for V_F and R. The forward speeds were designated as slow (SV_F), medium (MV_F), and high (HV_F); the radius of maximum winds were classified as small (SR), medium (MR), and large (LR). This notation, shown on Figure 2, indicates computed surge heights for locations given on the coast and various V_F - R combinations. Table 2 shows the values of R, V_F , and CPI for the respective locations indicated along the Texas Coast, and as originally given by Graham and Nunn. The values given by the table show that CPI and R vary throughout spatial range while prescribed values of V_F are independent of position.

TABLE 2

BETA HURRICANE PARAMETERS

Location	(in. Hg)	SR	MR	LR	Forward Speed (knots)		
					SV_F	MV_F	HV_F
					Slow	Medium	High
Port Arthur	27.54	7	14	27	4	11	28
Galveston	27.52	7	14	26	4	11	28
Bay City	27.49	6	13	25	4	11	28
San Antonio Bay	27.45	6	13	24	4	11	28
Sarita	27.38	6	12	23	4	11	28
Brownsville	27.28	6	11	20	4	11	28

5. Initial Generalized Surge Frequency

In the absence of more hurricanes of record, a generalized method is presented for deriving, at least to the first approximation, the open-coast surge frequencies. This simply means that all 19 hurricanes of record will be used initially to derive a surge-frequency relationship representative of the entire Texas Coast. To enable determination of the surge frequency for any specified position on the coast, a ratio of surge heights is employed. The ratio taken is the actual or observed surge height which occurred at some particular location to the surge height computed for the same location by the Bathystrophic Storm Tide technique. The surge height obtained analytically is chosen because the hurricane parameters are prescribed prior to carrying out the computations. With reference to Section II, paragraph 4 and Figure 2, the Beta Hurricane having parameters of LR and MV_F is selected (any other hypothetical parameters would be appropriate) for expressing the ratio. The ratio of the actual surge height to the preassigned hypothetical surge height will be designated hereafter as H/H_B . From the peak surge heights given in Table 1 and H_B values given on Figure 2, the exceedence frequency* per 100 events for the surge ratio is indicated by the circles shown on Figure 3. Curve 1 on the figure is a smooth line passing through the points. From Equations (1) and (2) or from Figure 1, frequency curves of surge heights at 50-mile intervals to the left and right of the peak surge were constructed and are shown as curves 2 through 8. The surge ratio probabilities, given by the eight curves on Figure 3, are mutually exclusive events. They may, therefore, be added to obtain the total surge-ratio probability representative of the entire coast, or stated mathematically, the probability frequency per 100 years for every H/H_B is given by

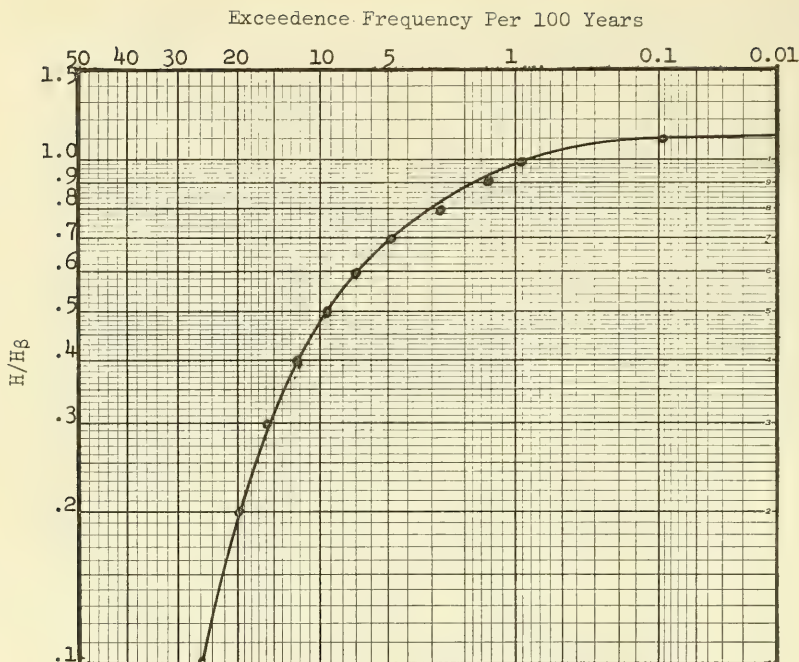
$$f = \frac{100 E (\Sigma f_r)}{Y (\Sigma \Delta X)} \quad (7)$$

Where E is the number of events (19 for this particular case), f_r the frequency ratios read from Figure 3, Y is the number of years of record used (66), and ΔX is the increments of distance along the coast employed. The total distance along the Texas Coast is 400 miles, therefore $\Sigma \Delta X = 8$ for the present problem. Figure 4 shows the results of these computations. Since H_B is known for the entire coast, the surge height H and associated frequencies can be evaluated for any position along the shoreline.

6. Surge Frequencies at Galveston, Texas

A question could be raised on the validity of the initial generalized frequency curve (Figure 4) derived, due to the relatively few events used; therefore, verification of the relationship is required. Of all the stations along the Texas Coast, Galveston has the most complete record of hurricane surge elevations, and based on these observations of record, this station was selected for carrying out the verification.

*Exceedence frequency - the percentage of values that exceed a specified magnitude.



H is the actual surge height

H_β is a Beta Hurricane surge height with parameters
Large Radius and Medium Forward Speed.

Figure 4. Initial Generalized Surge Frequency Texas Hurricanes

Curve 1 on Figure 5 shows the surge frequency at Galveston derived from the initial generalized frequency curve, and curve 2 shows surge frequency based only on those hurricanes affecting Galveston. Five hurricanes that crossed the Louisiana Coast and 12 that crossed the Texas Coast were used in the verification analysis. Equations (2) and (3) were used in estimating the surge heights at Galveston when recorded surge heights were unavailable. It is seen by comparing curves 1 and 2 on Figure 5 that for higher surges (greater than 6 feet above MSL) the maximum departure between the two curves is about 1 foot. Thus the two entirely different methods for deriving open-coast surge frequency are in reasonable agreement for the higher surges. Surges in the lower range, however, show considerable departure but this will be of no consequence because the surges in this range will be corrected in the final analysis to include nonhurricane surges. Adjustments made for the lower surges will be covered in subsequent paragraphs.

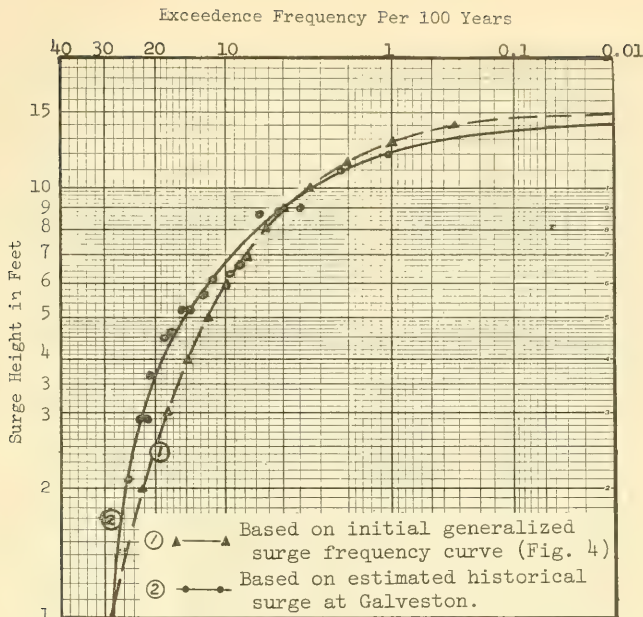


Figure 5. Hurricane Surge Frequency Comparison at Galveston, Texas

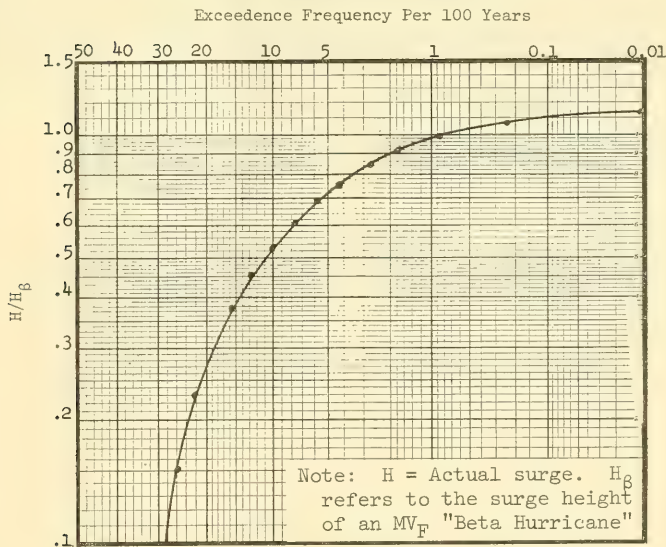


Figure 6. Generalized Hurricane Surge Frequency Texas Hurricanes

7. Final Generalized Surge Frequency

Because relatively few hurricane events are available for the surge frequency analysis, it would appear justifiable to envelope curves 1 and 2 on Figure 5 to provide a more conservative as well as reasonable hurricane surge frequency estimate. The enveloped curve, although not shown, was employed in reversal of the procedures to construct the generalized hurricane-surge frequency indicated on Figure 6. The relation shown on this figure pertains only to surge-height frequencies associated with full-scale tropical hurricanes; however, other factors can influence the lesser surge heights that make up the entire spectrum. These factors can be attributed to local meteorological conditions such as strong winds directed over the sea in a shoreward direction, tropical depressions, and peripheral hurricane surges. Nonhurricane surge heights above 2 feet MSL occur more frequently than those of similar magnitude associated with hurricanes, and therefore must be coupled with surge frequencies derived in the prior investigation to obtain a relationship consistent with the problem.

Because of the longer period of tide records available for Galveston, this station again was selected for making a surge frequency investigation of surges for all water level elevations equal to or exceeding 2 feet above mean sea level. The surge frequency curve derived from this analysis was combined with the one obtained from the final hurricane-surge frequency for Galveston. The two curves were connected at a point where the corresponding surge height was about 6 feet above mean sea level which indicates that surge heights above this elevation are generated only by tropical hurricanes. On the basis of this relationship and by reverting back to the generalized form, the final open-coast surge frequency estimate was obtained as shown on Figure 7. The surge frequencies at various locations along the Texas Coast derived from the final generalized surge frequency relationship is indicated on Figures 8 through 13. Figure 14 shows the surge heights along the coast that could be expected for corresponding exceedence frequencies of 5, 10, 25, 50, and 100 years.

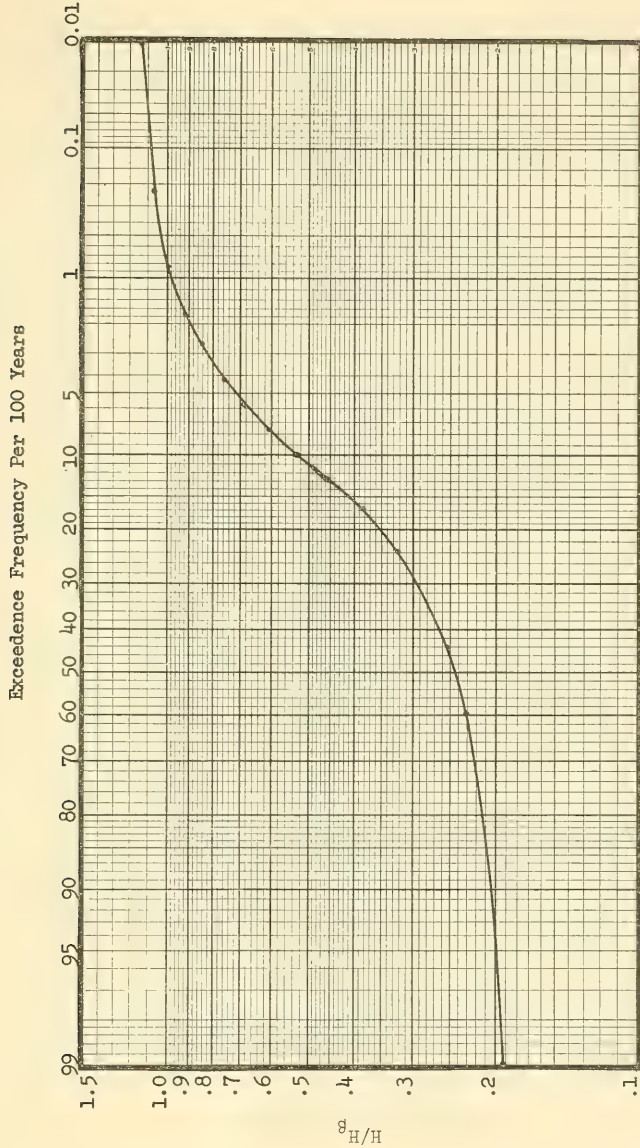


Figure 7. Final Generalized Surge Frequency - Texas Hurricanes

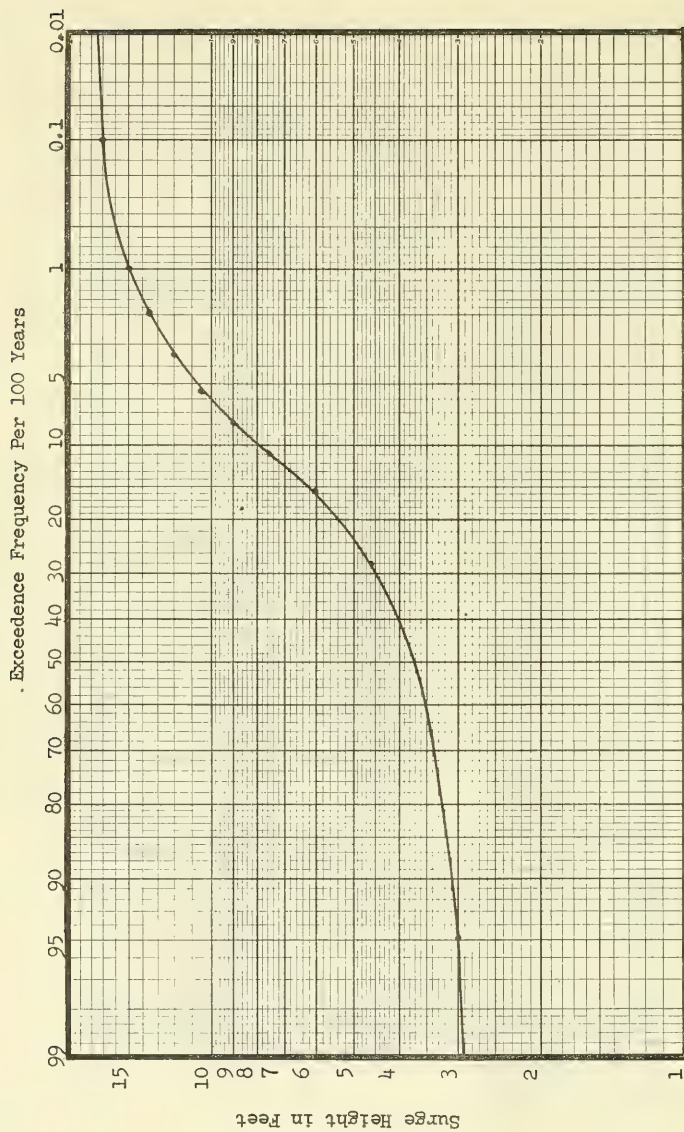


Figure 8. Surge Frequency on Open Coast - Sabine, Texas

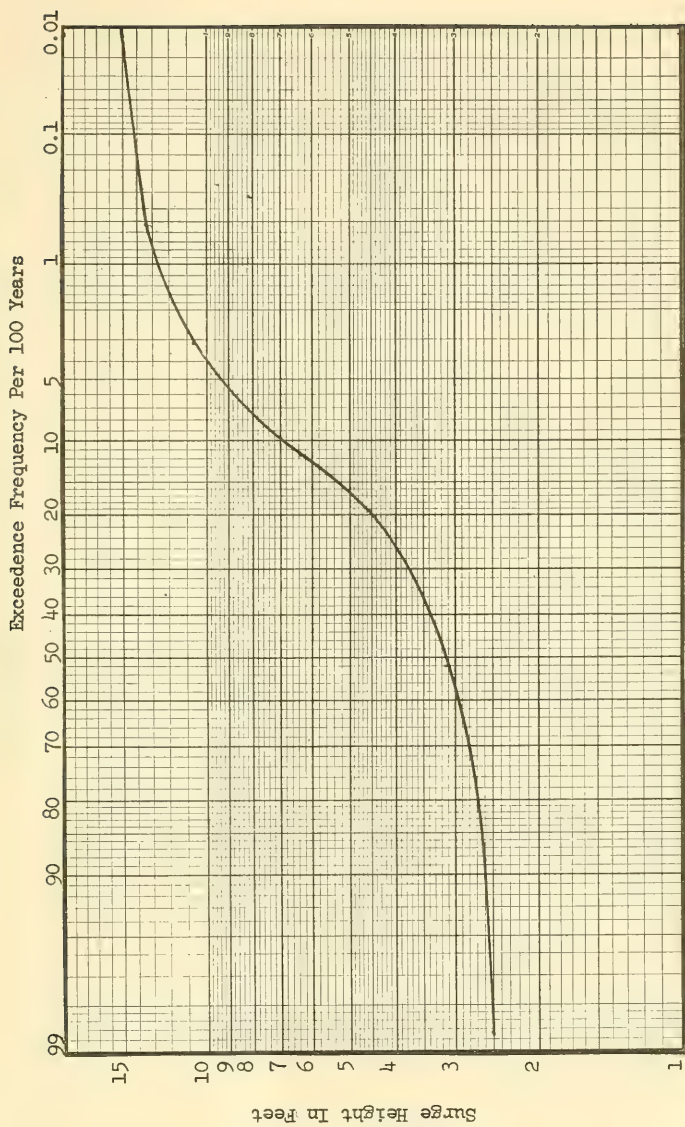


Figure 9. Surge Frequency on Open Coast - Galveston, Texas

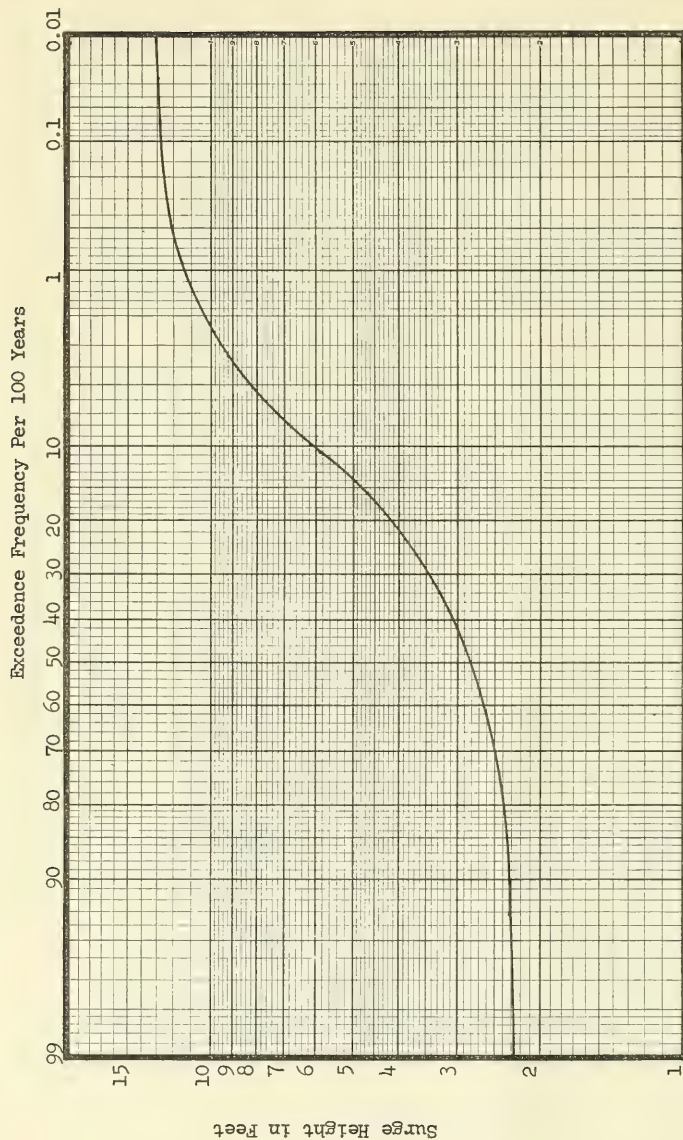


Figure 10. Surge Frequency on Open Coast - Freeport, Texas

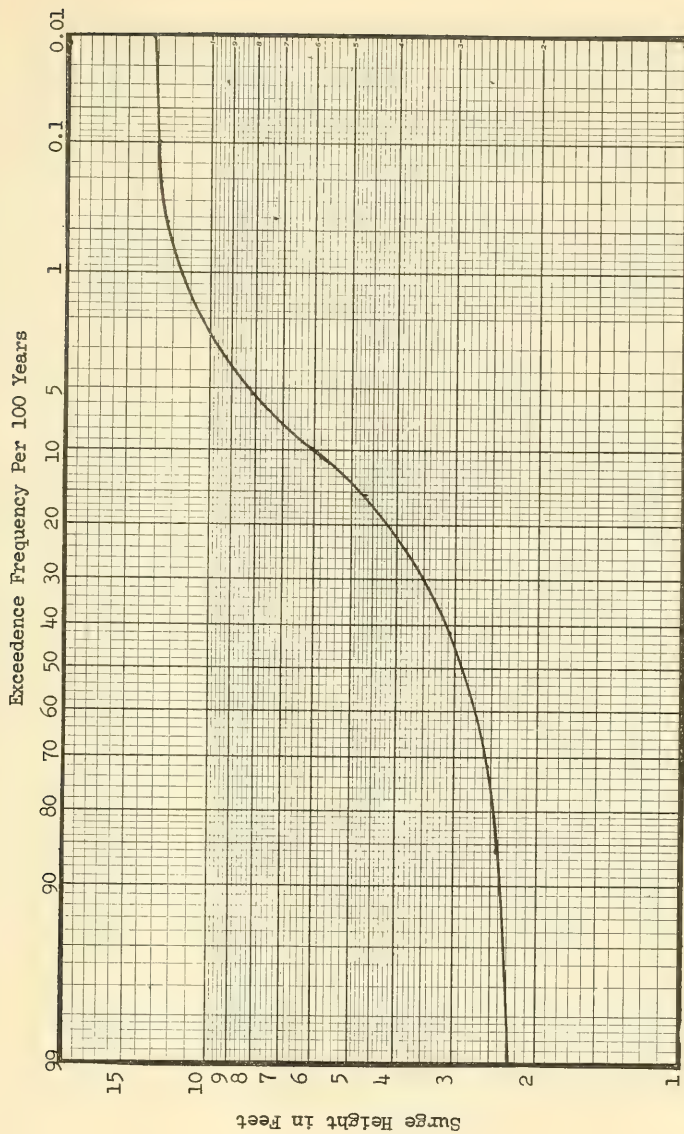


Figure 11. Surge Frequency on Open Coast - Port O'Connor, Texas

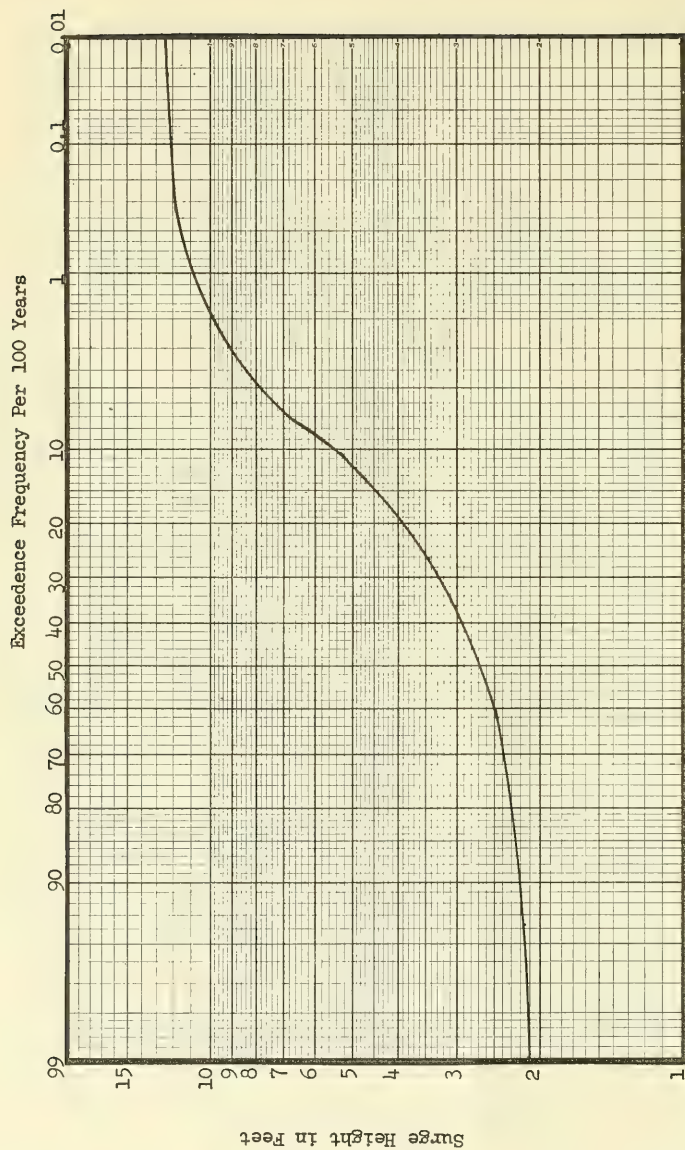


Figure 12. Surge Frequency on Open Coast - Mustang Island, Texas

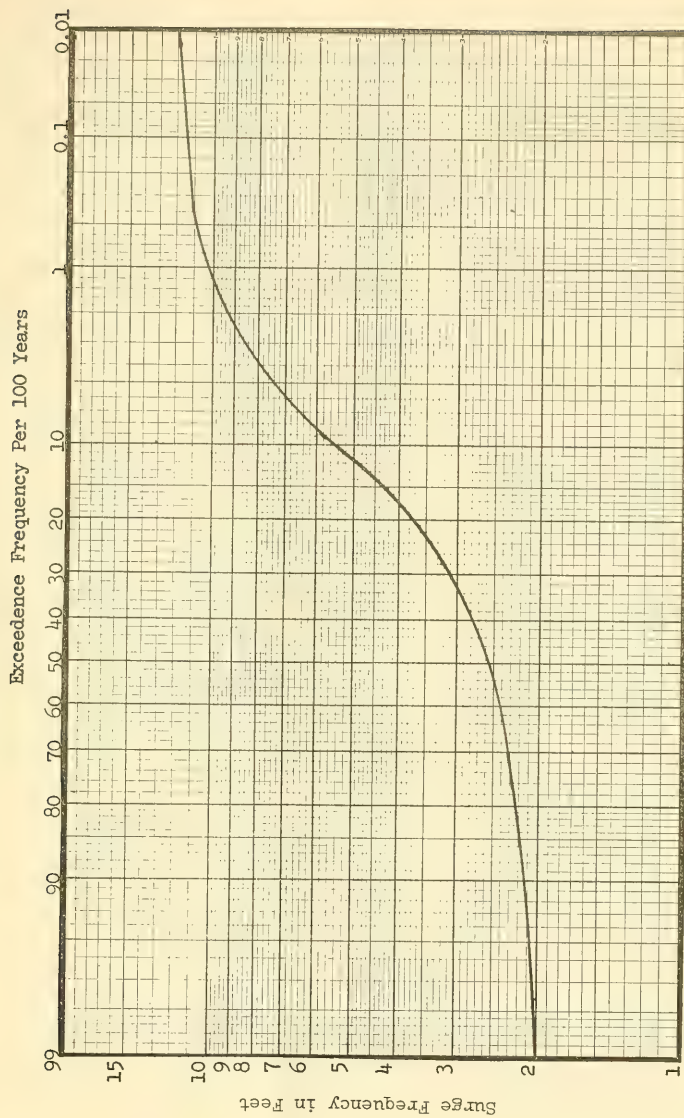


Figure 13. Surge Frequency on Open Coast - Port Isabel, Texas

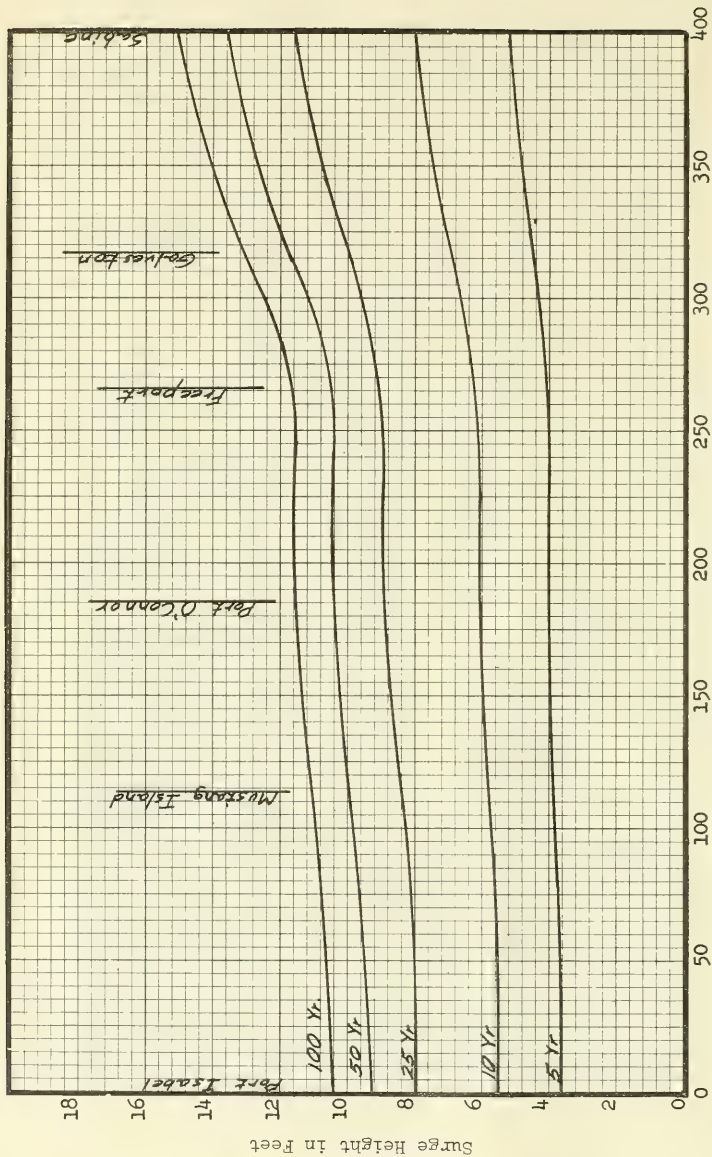


Figure 14. Surge Frequency Along the Texas Gulf Coast

1. General

It may be seen from the final generalized surge frequency relationship that the "Beta Hurricane" of large radius and mean forward speed, has a return frequency of about once in 100 years. This, however, gives no insight of frequencies of other "Beta Hurricanes" or in general all hypothetical hurricanes (all parameters variable) with prescribed parameters. Clearly it would be advantageous to assign probability frequencies to all hypothetical hurricanes possessing parameters reasonably characteristic of the area involved. It is not implied that all parameter combinations are important in connection with design of hurricane protection systems, but it would allow predicting the probable frequencies of the ones that are of interest. In the following paragraphs a method is presented for assigning frequencies to hypothetical hurricanes.

2. Probability Frequencies of Hurricane Parameters

Since the prescribed hurricane parameters (i.e., R, V_f , and CPI) are the only basis for predicting the hypothetical hurricane frequencies, then the actual probabilities of each parameter must be established. Based on the historical records given in Table 1, return frequencies of V_f , R, and CPI were constructed as shown on Figures 15, 16, 17, respectively. It appears that a forward speed of 11 knots is more frequent than those less than or exceeding this value, and accordingly the curve on Figure 15 was derived. A plot of R versus CPI, as mentioned previously, indicates there is a partial tendency for the radius of maximum winds to decrease with increasing intensity of hurricanes, and the return frequency of R was derived on this basis.

3. Probable Storm Frequencies

It would be more appropriate in deriving hypothetical hurricane frequencies to study the influence of the parameters by the statistical method of joint distribution if sufficient events were available for such an analysis. However, the actual recorded events are limited in number; therefore, an alternate solution must be obtained. If it is assumed, for the present, that all variables are statistically independent, one can resort to an elementary mathematical principle of simultaneous events. This principle essentially states that if one event occurs h ways, and another j ways, then the two events occurring simultaneously will occur $h \times j$ ways. To account for the partial dependence of R to CPI and other unknown factors, and based on the above principle, it will be assumed that the hurricane probability frequency P, expressed in events per 100 years, can be written in the form:

$$P = K (f_r)_R (f_r)_{CPI} (f_r)_{V_f} \left(\frac{N}{Y}\right) 100 \quad (8)$$

where N is the number of events, Y is the years of record, and K is the

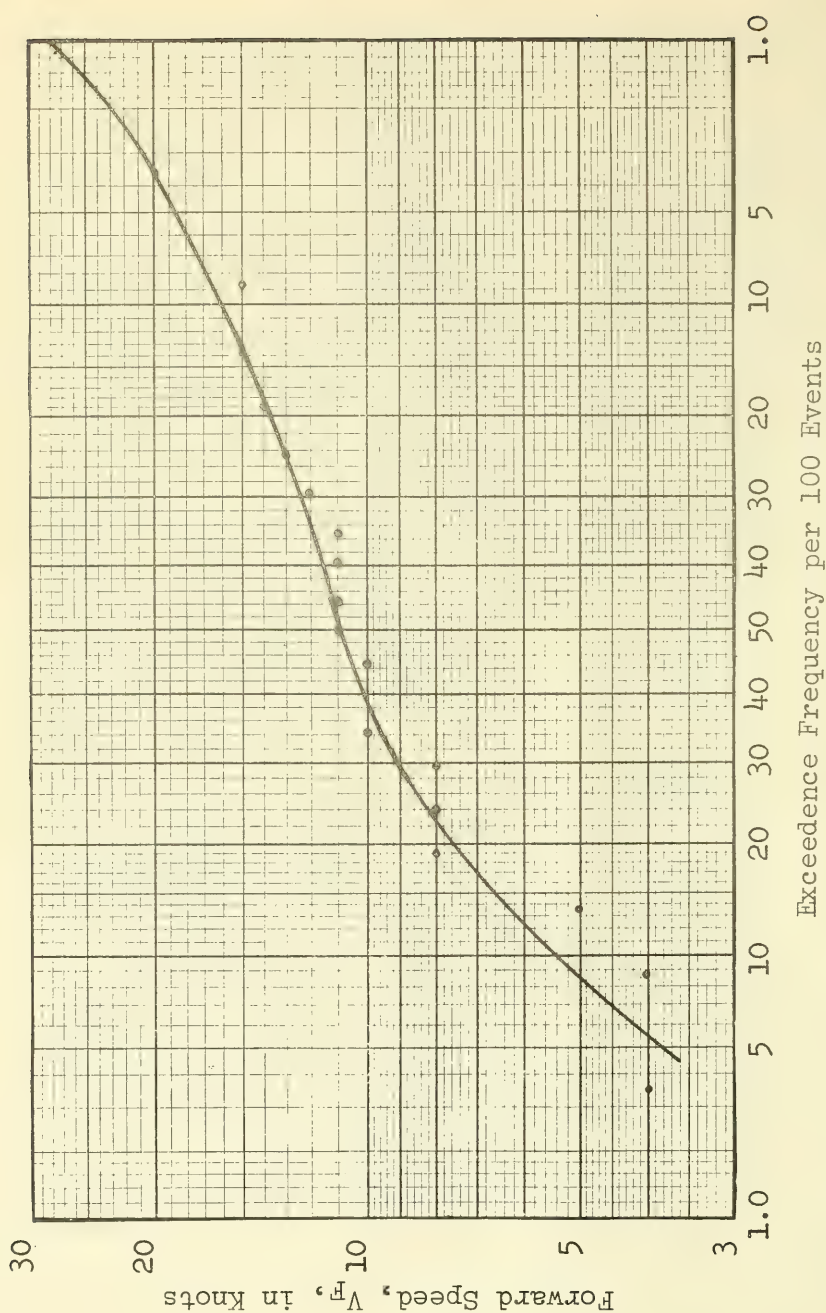
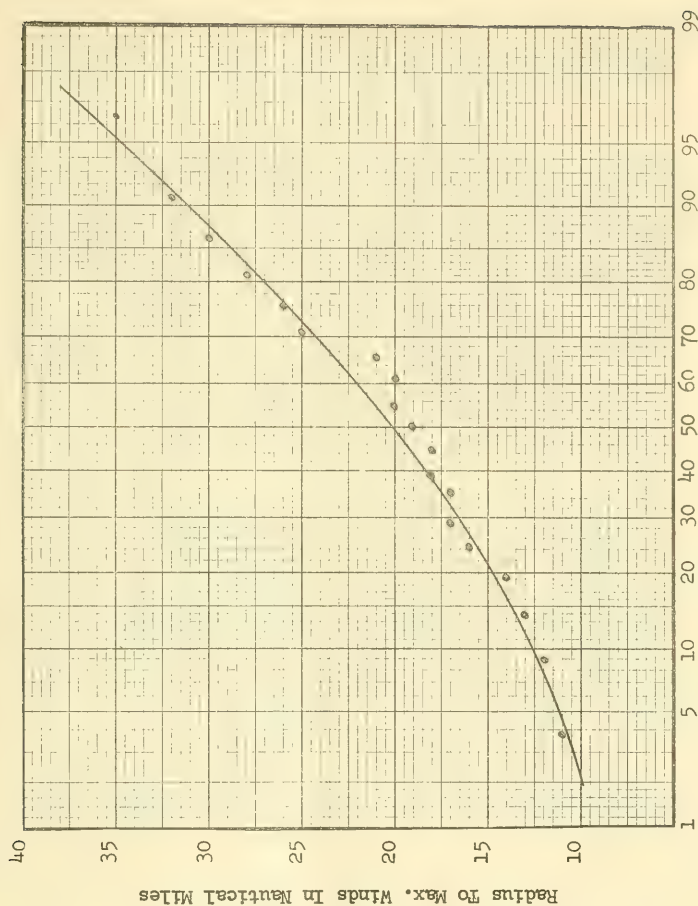


Figure 15. Frequency of Translation Speeds for Texas Hurricanes
Horizontal scale altered from normal log-log scale



Exceedence Frequency Per 100 Events

Figure 16. Frequency of Radii for Texas Hurricanes

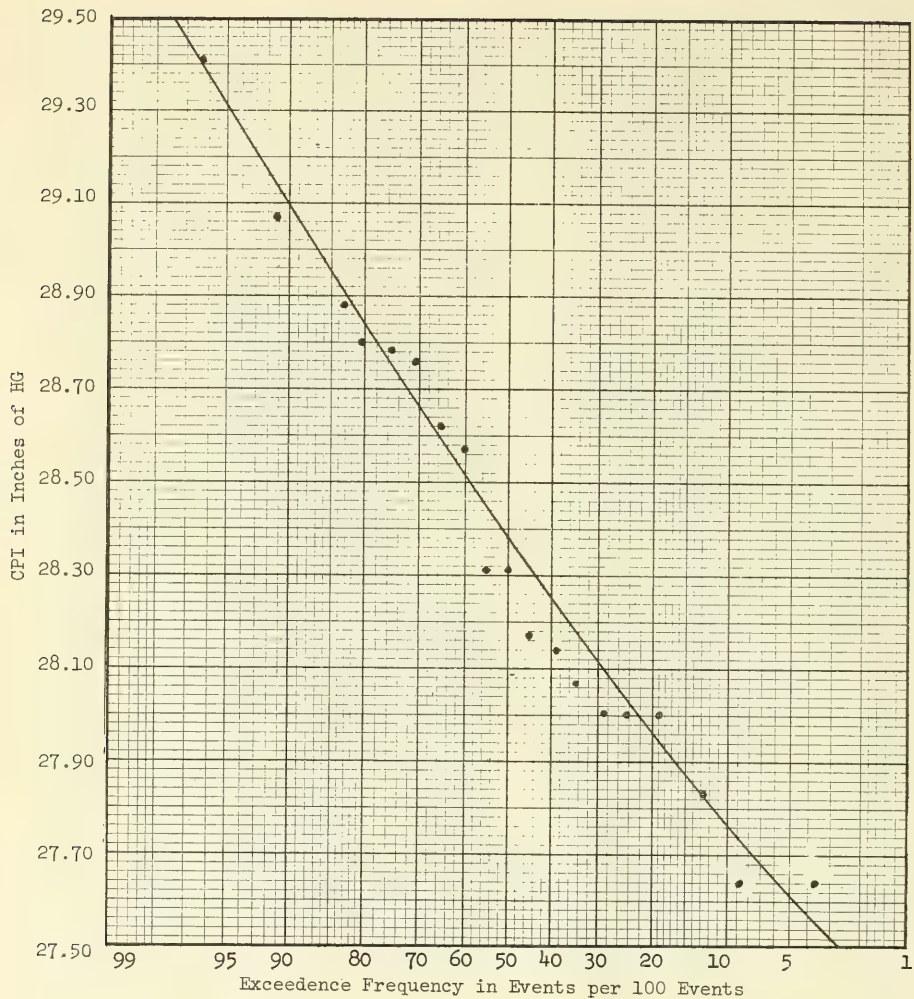


Figure 17. Frequency of Hurricane CPI for Texas Gulf Coast

proportionality constant dependent upon the coastal position. For example, K may be determined for the open coast in the vicinity of the San Antonio Bay region by considering the "Beta Hurricane" of large radius (LR) and medium forward speed (MV_F) (see Table 2). The values of CPI, R and V_F are 27.45, 24, and 11, respectively. From Figures 15, 16, and 17, the corresponding frequency ratios are 0.02, 0.69, and 0.5, respectively. Equation (8) gives:

$$P = K (0.69) (0.5) (0.02) \left(\frac{19}{66}\right) 100 = .1987K$$

K now may be evaluated since P has been determined previously from the generalized frequency analysis and has a value of about 0.985. Hence K is equal to about 4.96, and is taken to be constant for this specific location. With the known proportionality constant, all other hypothetical hurricane frequencies may be evaluated including any storm of record. For example, the return frequency of the severe storm of 1961 (Carla) which occurred near this position (taken to be the exact location) can be evaluated and given by:

$$P = (4.96) (0.765) (.055) (.058) \left(\frac{19}{66}\right) (100) = 0.35 \text{ events per 100 years.}$$

This equation indicates that a storm equivalent to Hurricane Carla may occur about once every 289 years. The probability frequencies are tabulated for all hurricanes in Table 1. Note that all frequencies do not appear to be consistent with the severity of the storm - for example, the 1915 storm. However, it must be remembered that a hurricane which produces a high surge on the open coast is not necessarily a very infrequent one, since each parameter contributes to its probability of occurrence. Surely, errors are also involved in the prediction scheme and certainly the parameter magnitudes given are only an approximation, particularly those recorded in the early part of the century. In any event, Equation (8) should give a reasonable approximation of the hurricane frequencies that can be expected by actual occurrences.

The advantage and the primary importance of Equation (8) allow one to assign frequencies to hypothetical hurricanes of prescribed parameters. The relation does not indicate the storm surge frequency associated with the hurricane, but merely indicates the frequency of the tropical cyclone. This can only be useful to coastal engineers in resolving design problems where a hurricane frequency criterion must be established.

Section IV. REGRESSION ANALYSIS

Although not used in connection with the present study, the technique of Multiple Linear Regression Analysis was employed in an attempt to correlate the hurricane parameters and basin characteristics with the open-coast peak surge height. None of the correlation results obtained were satisfactory; the final relation derived is presented only for the purpose of comparison by subsequent similar investigations. The first attempt to find the correlation of the variables was made at the U. S. Army Corps of Engineers, Hydrologic Engineering Center, Sacramento, California.

(Beard, 1966). However, the results obtained indicated that forward speed of the hurricane had only a negligible effect on the open-coast surge buildup. This, of course, contradicts the more sophisticated analytical schemes for predicting the open-coast surge height, and also disobeys the laws of motion.

The author first believed that the method of defining the forward speed as the average speed, two hours before and two hours after landfall, was causing the difficulty. Therefore, based on the time histories of the 19 hurricanes used in this report, a study was made by defining the forward speed as the average speed over the Continental Shelf and these speeds were estimated. These average forward speeds were used instead of the ones given in the above reference; the results of this analysis, however, indicated the same contradiction that had obtained before. It was concluded that the discrepancy must be due to data acquired from Texas hurricanes; therefore, five Louisiana hurricanes and the 13 Texas hurricanes used for deriving the open-coast surge frequency at Galveston, Texas, were used in a separate regression analysis. Again, the results indicated that forward speed has little significance on the open-coast surge buildup. Consequently, it was assumed that the limited data did not provide the necessary information for carrying out this type of analysis.

In all three investigations using multiple correlation analyses, it was found that the surge-height may be estimated approximately by

$$H = 0.26 (\Delta P \times R)$$

where H = Surge height in feet, $\Delta P = 29.92 - \text{CPI}$ = the difference between the normal pressure and central pressure index in inches of H_g , and R = Radius of maximum winds in nautical miles. The coefficient of correlation for this relation is approximately 0.75, as found by the three attempted investigations.

Section V. BAY SURGE FREQUENCIES

1. General

Surge height frequencies within a semienclosed bay system are more difficult to predict than those on the open coast. Virtually no surge height records are available for the Texas estuaries and adjoining low-lying terrain; the available records at a few locations do not give any indication of the actual surge heights experienced at other positions in the system. The water surface may vary throughout the entire spatial range, and the vertical departure of the free surface is dependent upon the magnitude of the forcing functions involved. The water level elevations reached at various positions in the system are also affected by direct rainfall on the water surface, and rainfall runoff entering the bay from the surrounding terrain and local streams. Surge heights at each position are also dependent upon basin configuration, basin depths,

energy dissipation, and radiational loss of energy from the bay to the sea. To estimate the surge height frequencies at various positions in the system, it is necessary to take those water levels determined by numerical methods for hurricanes of prescribed parameters. This will allow assigning frequencies to the surge heights reached at all positions in the system because by the method presented previously the return frequencies of the various hypothetical hurricanes can be determined. Reid and Bodine (1967) presented a finite-difference scheme for predicting the surge heights at discrete positions in a bay system, and based on this treatment, the water level elevations were computed for various storms superimposed over Galveston Bay. Parametric studies in connection with the scheme allow prediction of the surge height frequencies at various positions in this bay, and can be carried out for any bay system.

2. Prediction Method

Hurricane surge heights in a bay are influenced by the path that the storm takes with respect to the system. That is, a storm passing to the left of a semiencllosed body of water on the Texas Coast will cause the water to pile up in the upper region of the bay, while those passing to the right depress the surge. This introduces an additional complexity in evaluating the bay surge frequencies, but will be disregarded in order to get a more conservative surge-frequency estimate that will take into account all of the uncertainties of the problem. If one treats the problem on the relative basis considering the water levels in the bay change relative to those on the immediate open coast and associated with identical frequency of occurrences, then a simple scheme may be devised. In other words, the bay surge frequency is the adjacent open-coast surge frequency shifted to correspond with a particular hurricane frequency and known computed surge height. Again the "Beta Hurricane", with parameters LR and MV_F , is selected for performing the shift. For example, it was found from the numerical computations of the Galveston Bay system that the peak surge for the above hypothetical hurricane was 16 feet above MSL for a position near Baytown, Texas. Based on the known surge frequency of about once in 100 years and the 16-foot elevation, a point can be established on a graph with log-log probability paper. This, however, would give only a single point on the graph. But if it is assumed there is a relative similarity between the surge frequency curve derived on the open coast and the one in the bay, then one could approximate the entire surge frequency curve by considering it parallel to the one for the open coast.

Figure 18 indicates the frequency of surge heights for Baytown by performing this operation. This simply implies that the curve obtained on Figure 18 is the curve indicated on Figure 9 shifted upward to pass through the point corresponding to 16 feet on the ordinate scale and about once in 100 years on the abscissa scale. Log-log probability paper must be used in carrying out this scheme because it gives the lesser surge heights more reasonable values for the associated frequencies. This scheme will allow surge frequency relationships to be determined for all positions within any bay system and the low-lying terrain if the surge heights are known in advance from previous numerical computations.

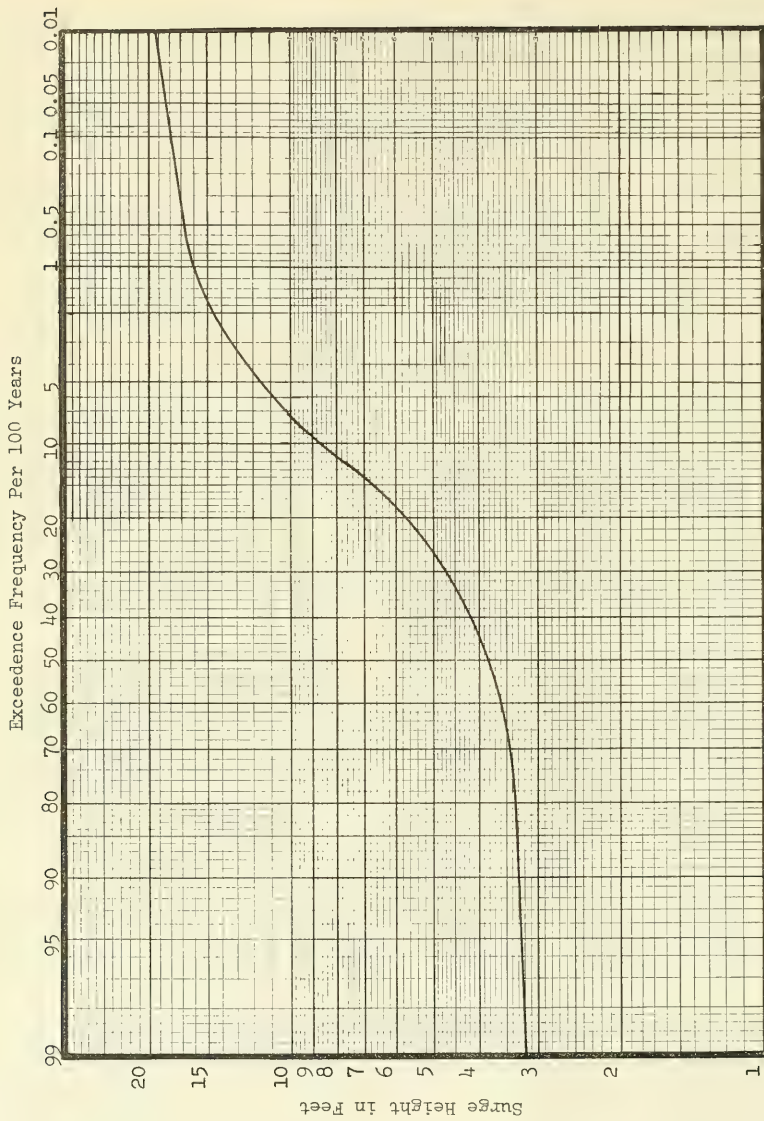


Figure 18. Bay Surge Frequency at Baytown, Texas

The surge frequencies of various hypothetical hurricanes within the bay system should be interpreted with care because a very infrequent hurricane will not necessarily produce a higher surge than those more frequent. For example, numerical computations in Galveston Bay have shown the highest surge for "Beta Hurricanes" was obtained by the LR - SV_F in the upper regions in the bay, LR - MV_F in the mid regions of the bay, and LR - HV_F at the lower regions of the bay.

Section VI. CONCLUSIONS

The hurricane and surge frequency estimates presented, although considered adequate for the present, are subject to extensive improvement upon availability of additional events. A reasonable degree of conservatism has been employed throughout the analysis to account for limited insight of the probable frequencies. The Texas open-coast surge frequencies are considered more reliable than those in estuaries because more surge records were available for deriving the surge frequency relationships.

The relationships derived in this report apply only to the Texas Coast and must *not* be applied to other localities. The methods, however, could be used for any other coastal zone if one proceeds through steps similar to those presented, but using factors characteristic to the zone under consideration.

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